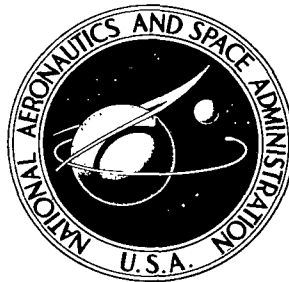


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INFLUENCE OF ALUMINUM ON FRICTION AND WEAR OF IRON-ALUMINUM ALLOYS DRY AND LUBRICATED

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16. Abstract Sliding friction experiments were conducted with iron-aluminum alloys, unlubricated and lubricated, in an argon atmosphere. The alloys contained 10-, 20-, 25-, and 50-atomic-percent aluminum. Friction and wear were measured for dry sliding, sliding in hexadecane, and sliding in hexadecane containing various concentrations of stearic acid. Results of the study indicate that the addition of 10-atomic-percent aluminum to iron results in an increase in friction and wear in dry sliding and when hexadecane is present. The aluminum undergoes equilibrium segregation to the surface. Aluminum increases surface reactivity with stearic acid. Order-disorder reactions were masked by surface segregation effects.		
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INFLUENCE OF ALUMINUM ON FRICTION AND WEAR OF IRON-ALUMINUM ALLOYS DRY AND LUBRICATED

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SUMMARY

An investigation was conducted to determine the influence of aluminum on the friction and wear behavior of iron. Unalloyed iron, as well as iron alloys containing 10-, 20-, 25-, and 50-atomic-percent aluminum were examined. The 25- and 50-atomic-percent alloys were examined in the ordered and disordered state. The alloys were examined with a hemispherical pin sliding on a disk. They were examined unlubricated, in hexadecane, and in hexadecane containing various concentrations of stearic acid. Auger analysis was used to determine the nature of the alloy surface.

Results of this study indicate that aluminum in iron markedly alters its friction and wear behavior. With the unlubricated 10-atomic-percent-aluminum alloy, an increase in both friction and wear was observed when compared with iron. With stearic acid, the presence of aluminum in the alloy increased surface reactivity. The aluminum was observed to undergo equilibrium segregation to the alloy surface. With only 10-atomic-percent aluminum in the bulk, the alloy surface had an aluminum concentration of 80 percent. The order-disorder reactions in Fe_3Al and FeAl did not affect friction and wear.

INTRODUCTION

Iron-base alloys are the most widely used class of materials in the fabrication of components for lubrication systems. The influence of specific alloying elements in iron on such properties as adhesion, friction, and wear in the presence and absence of a lubricating media is, however, not clearly understood. The effect of such elements as carbon, sulfur, phosphorus, chromium, antimony, silicon, and aluminum is of interest.

The influence of aluminum on the friction and wear behavior of iron is of particular interest because when it is in the proper concentrations in iron, alloys exhibiting ordering can be obtained (refs. 1 to 3). Ordered alloys of copper-gold (ref. 4) and iron-cobalt

(ref. 5) have been shown to have desirable friction and wear characteristics. Aluminum exhibits very strong adhesive behavior toward iron (ref. 6), which may influence its effect on friction and wear when alloyed with iron. It is also very chemically active and may increase surface reactions with lubricants. Studies with aluminum in copper indicate that its presence in copper improves lubrication with a fatty acid (ref. 7).

This investigation was conducted to determine (1) the nature of the surface of iron-aluminum alloys, (2) the friction and wear behavior of such alloys in the absence and presence of a lubricant, and (3) the effect of order-disorder reactions on the friction and wear of Fe_3Al and FeAl . Initial analysis of alloy surfaces was made with Auger Emission Spectrometry to determine the 10-percent-aluminum alloy's surface composition (ref. 8). Friction and wear experiments were conducted with a pin sliding on a rotating disk. Various iron-aluminum alloys were examined in sliding contact with themselves. Measurements were made in argon and in the presence of a lubricant. The lubricant was stearic acid in hexadecane.

MATERIALS

The iron-aluminum alloys used in this study were prepared from 99.99-percent iron (zone refined) and 99.99-percent aluminum. The alloys were vacuum melted in magnesium oxide crucibles and were poured into water-cooled copper molds. Castings were electron discharge machined (EDM) into specimens and were then heat treated to ensure uniformity of grain size.

The hexadecane used as a solvent for stearic acid was 99+ percent pure and was olefin free. It was percolated through activated aluminum just prior to use. The stearic acid was reagent grade. The argon gas employed as a blanketing gas was obtained from boiling liquid argon (maximum 1.0 ppm oxygen and 7.0 ppm water).

EXPERIMENTAL PROCEDURE

Ordering

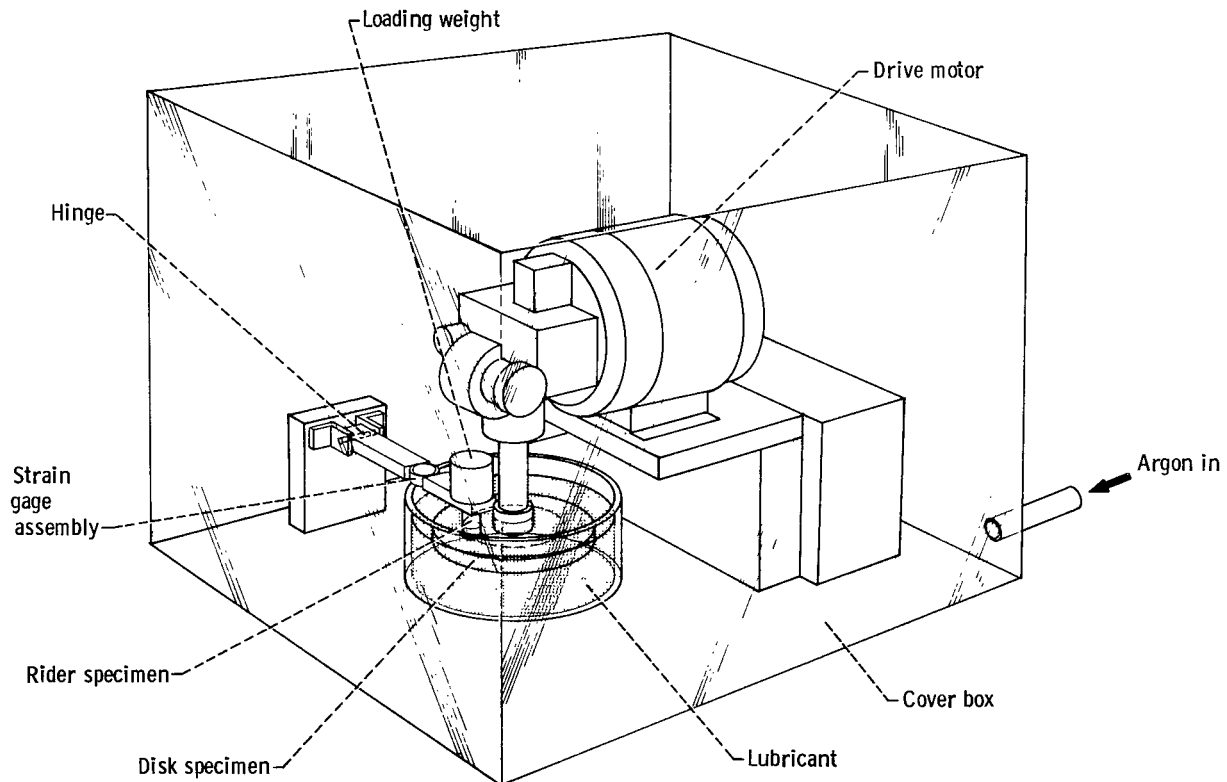
The procedure for obtaining ordering was taken from the literature (refs. 9 to 11). For example, with Fe_3Al it involved heating for 1 hour at 800°C , 1 hour at 500°C , and 10 hours at 300°C . The maximum degree of order achievable is from 0.8 to 0.85 (refs. 10 and 12). X-ray analysis was used in this investigation to determine ordering.

Friction Specimens

Pin and disk specimens of the same alloy were polished on metallurgical papers to 600 grit. They were further polished with diamond paste. Alumina in water was the final polish and the specimens were then rinsed with distilled water and finally alcohol before use.

Argon Environment

All experiments were conducted under a Lucite box in which a positive argon pressure was maintained (fig. 1). After the specimens and lubricant were placed in the apparatus, the box was purged with argon for 20 minutes prior to the start of each experiment. The Lucite box had a volume of 0.3 cubic meters and the argon flow rate was such as to result in a complete argon replacement three times a minute.



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Figure 1. - Friction apparatus.

Auger Emission Spectroscopy

A sample specimen for Auger analysis was obtained from the same casting as the disk and pin specimens. The specimen was mounted in the Auger vacuum chamber, which was evacuated to 10^{-10} torr. The specimen surface was ion (argon) sputter cleaned. An Auger trace was obtained after cleaning and removal of alloy surface layers. Tracings were obtained again after the specimen had been heated to 500°C and held at that temperature for 1 hour.

RESULTS AND DISCUSSION

Auger Analysis

Recent adhesion and Auger Emission Spectroscopy studies have indicated that very small concentrations of aluminum in copper undergo equilibrium segregation to the surface, resulting in surface concentrations of aluminum far in excess of bulk concentrations (refs. 8 and 13). This segregation influences adhesion and therefore can be expected to influence friction and adhesive wear. It was anticipated, based upon iron-aluminum alloy oxidation studies where the alloy surface was aluminum oxide rich (refs. 14 to 17), that the same process might be occurring in iron-aluminum alloys.

Auger Emission Spectroscopy (hereinafter AES) was used to examine an iron - 10-atomic-percent-aluminum alloy surface to determine if surface segregation of aluminum occurs. The results obtained in these experiments are presented in figures 2(a) to (d). Figure 2(a) is an AES trace in the electron energy range of 100 to 1500 electron volts. The trace reveals the presence of iron peaks. Figure 2(b) is an AES trace in the range of 50 to 70 electron volts revealing the aluminum peak. These AES traces were obtained from the alloy surface after the surface had been sputtered for 2 hours with argon at an ion gun current of 4×10^{-6} amperes and 700 electron volts.

The sputtered-clean surface was heated for 1 hour at 500°C . After heating and subsequent slow cooling to room temperature, the AES traces of figures 2(c) and (d) were obtained. These traces are analogous to those of figures 2(a) and (b), only showing the effect of heating on the changes in the surface layers. A comparison of figures 2(c) and (d) with figures 2(a) and (b) indicates that the aluminum Auger peak has increased considerably, relative to the iron peak, as a result of heating.

If the ratio of the aluminum peak to the iron peak after sputtering is compared to the ratio of the same two peaks after heating, an indication of surface coverage can be obtained. Such a comparison reveals an aluminum surface concentration of approximately 80 percent (see ref. 8 for the details of this determination). This means that the aluminum surface concentration is eight times the bulk concentration. Aluminum in iron

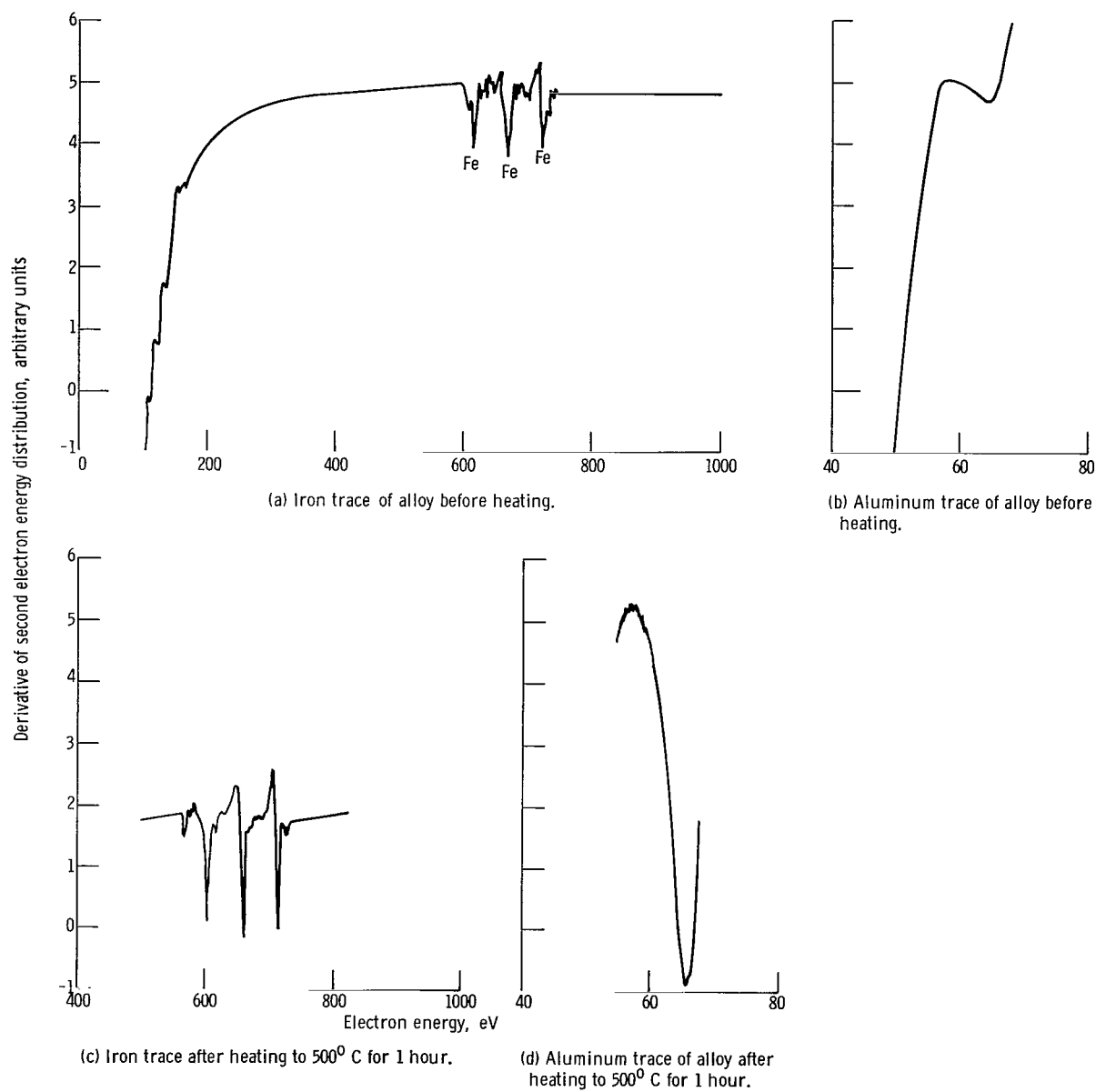


Figure 2. - Auger emission spectrometer trace of 10-atomic-percent-aluminum - iron alloy.

undergoes equilibrium segregation to the surface just as it does in copper, only to a greater extent. With 10-atomic-percent aluminum in copper, heating to 500^o C resulted in 55 percent surface coverage with aluminum (ref. 12). This difference may be due to the greater amount of unoccupied free volume of the body-centered-cubic structure relative to the more dense face-centered-cubic system.

Dry Sliding

Friction and wear experiments were conducted in an argon atmosphere with iron containing various amounts of aluminum, and the results obtained are presented in figure 3. The first observation to be made from the data is that the presence of 10-atomic-percent aluminum in iron results in an increase in both friction and wear. These results are analogous to those obtained with copper-aluminum alloys. The presence of aluminum resulted in an increase in adhesion (ref. 13).

At aluminum concentrations beyond 10 atomic percent, the wear began to decrease.

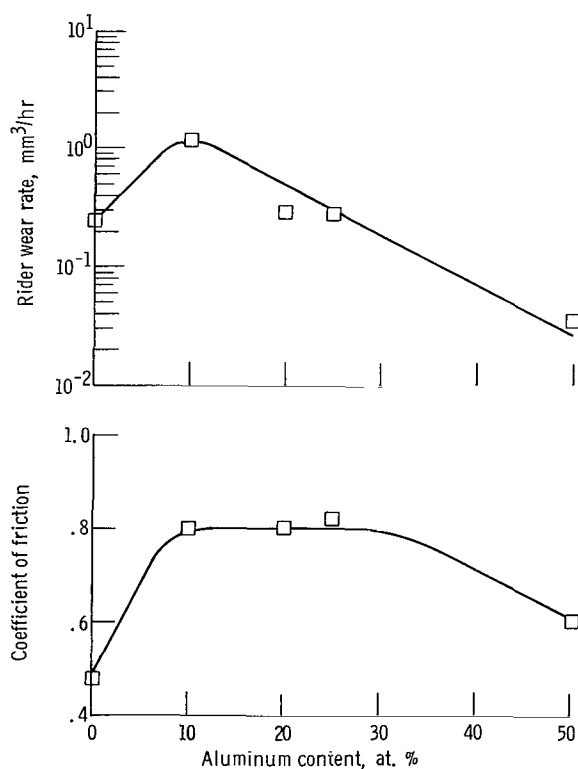


Figure 3. - Coefficient of friction and rider wear rate for iron containing various amounts of aluminum. Sliding velocity, 3.8 centimeters per second; load, 250 grams; 23° C for 1 hour in an argon atmosphere.

The 50-atomic-percent-iron - 50-atomic-percent-aluminum alloy exhibited the lowest friction and wear of the alloys. It can be said that in dry sliding in an argon environment the presence of aluminum (<50 at. %) adversely influences friction. The bulk alloy mechanical properties change markedly at the higher concentrations of aluminum and this may account for the decrease in friction with the 50-atomic-percent alloy.

These observations are consistent with the Auger analysis, earlier adhesion studies (refs. 6 and 13) and friction studies (ref. 18); that is, the friction of an aluminum surface is greater than that of an iron surface. Here, however, the aluminum is not bulk aluminum but rather a surface layer and the logical question is whether it (aluminum) behaves in the same manner when on a predominantly iron substrate. In an attempt to answer this question the unalloyed iron substrate used in figure 3 was ion plated with less than 200 angstroms of aluminum, and a friction experiment was conducted on that surface. The results obtained are presented in figure 4.

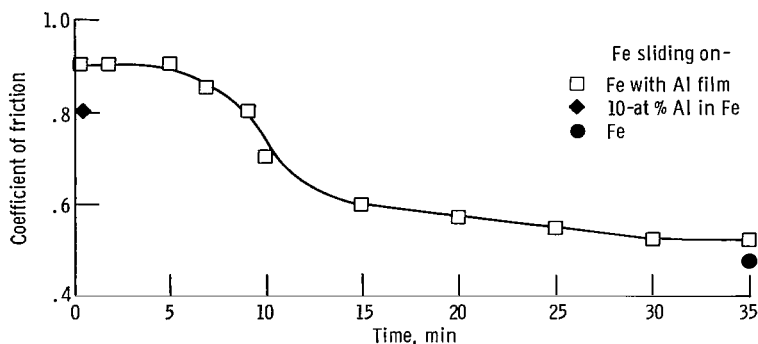


Figure 4. - Coefficient of friction for iron sliding on iron with an ion-plated aluminum film (<200 Å). Sliding velocity, 3.8 centimeters per second; load, 250 grams; 23° C for 1 hour in an argon atmosphere.

In figure 4 the friction coefficient for the aluminum-coated iron surface is plotted as a function of time. The friction coefficient starts at 0.9 and decreases ultimately to a value of 0.53 after 35 minutes of sliding. The high initial friction coefficient reflects the influence of aluminum on sliding friction behavior. With repeated passes over the same surface the aluminum surface layer is worn away; and as more and more iron is exposed, the friction coefficient decreases to a value eventually approaching that of iron. The friction coefficient does not reach the value of iron because with wear more aluminum on the surface and adjacent to the wear track is brought into the contact zone. The initial value is higher than that of the iron-aluminum alloy because the surface is all aluminum; whereas with the alloy, as indicated by Auger analysis, only 80 percent of the surface layer consists of aluminum.

The Auger analysis revealed that when the specimen of iron-aluminum containing 10-atomic-percent aluminum was heated to 500° C, aluminum surface coverage was

80 percent. In dry sliding friction experiments at higher sliding speeds than used in this study, temperatures at the interface (flash) of 700^o to 1000^o C have been measured (refs. 18 and 19). The general surface temperature will be considerably below this value and will be a function of load and speed of sliding.

Elements, such as aluminum, which expand the crystal lattice of iron will diffuse much faster than elements which contract the lattice. Both types of diffusion are, however, faster than self-diffusion of the solvent iron. The plastic deformation occurring at the interface and associated with sliding can markedly increase the diffusion of aluminum to the surface. Compressional stresses can increase the self-diffusion of iron a thousandfold at strain rates as low as 2×10^{-3} per second and this reduces activation energy for diffusion (ref. 20). Thus, the interfacial temperatures during sliding could be considerably below 500^o C, and 80-percent surface coverage with aluminum could still result.

No attempt was made in these studies to determine at what minimum temperature equilibrium segregation would occur. Earlier studies with copper-aluminum alloys indicate that it occurs at temperatures as low as 200^o C (ref. 8).

Ordering

There are two iron-aluminum systems that exhibit ordering. These exist in the composition ranges of Fe₃Al and FeAl. Studies with the FeCo system have indicated that ordering can favorably influence friction and wear (ref. 5). The alloy compositions Fe₃Al and FeAl were therefore examined in the ordered and disordered states. Figure 5 indicates the atomic arrangement of the iron and aluminum atoms in these states.

In figure 5(a) the arrangement is disordered; that is, any particular site may be occupied by either an iron or aluminum atom. Figure 5(b) indicates long-range order, where there is essentially a cubic structure within a cube. The outer cube consists entirely of iron atoms, while the inner cubic structure can consist of either. Figure 5(c) shows the ordered lattice, or superlattice, of Fe₃Al, in which no two aluminum atoms would be closest neighbors at a distance of $a\sqrt{3}/2$ and no two aluminum atoms would be second closest neighbors at a distance of a . The FeAl-ordered structure is presented in figure 5(d). In this structure the outer cube is completely occupied by iron atoms and the inner cube by aluminum atoms.

The friction and wear properties of the ordered and disordered alloys Fe₃Al and FeAl are presented in table I. Ordering appears to have little effect on friction and wear for both Fe₃Al and FeAl. These results are in sharp contrast to results obtained earlier with copper-gold alloys (ref. 4) and iron-cobalt alloys, where ordering markedly decreased both friction and wear.

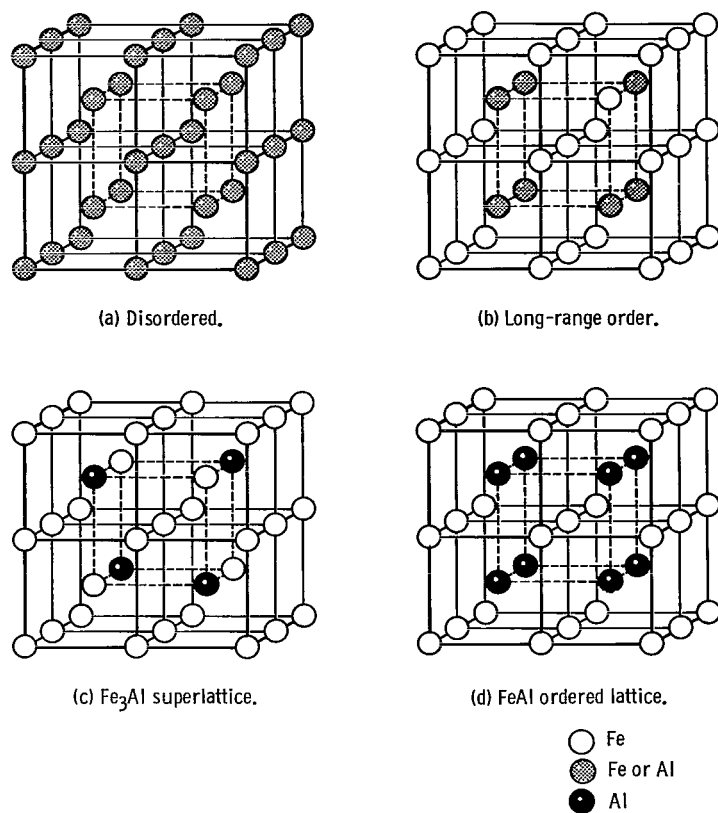


Figure 5. - Atomic structure of iron-aluminum alloys.

TABLE I. - EFFECT OF ORDERING ON FRICTION AND WEAR
 OF IRON-ALUMINUM ALLOYS

[Sliding velocity, 3.8 cm/sec; load, 250 g; 20° C for 1 hr in argon.]

Atomic state	Alloy	
	25-Atomic-percent aluminum	50-Atomic-percent aluminum
Ordered:		
Coefficient of friction	0.80	0.65
Rider wear rate, mm ³ /hr	5.00×10 ⁻¹	2.15×10 ⁻²
Disordered:		
Coefficient of friction	0.85	0.60
Rider wear rate, mm ³ /hr	6.72×10 ⁻¹	3.44×10 ⁻²

There are two explanations which may account for the absence of an effect on friction and wear as a result of ordering. The first is that the mechanical properties of the alloys are not markedly affected by ordering (refs. 2, and 21 to 23). There have been reports indicating that high-aluminum-content alloys were brittle. Studies have indicated, however, that brittleness of Fe-Al solid solutions containing 25- to 50-atomic-percent aluminum is related to the gathering of impurities during solidification at the grain boundaries (ref. 24). This can be prevented by the use of high-purity materials. Extension values of 11 percent have been obtained at room temperature for 40-atomic-percent aluminum - iron alloys (ref. 24). Slip is basically the same as in iron and iron-silicon alloys, about 80 percent on {110} planes, 16 percent on {211} planes, and 4 percent on {321} planes (ref. 25).

The second reason for the similarity in friction and wear in table I for Fe_3Al and FeAl in the ordered and disordered states may be the strong influence of the surface-segregated aluminum. As already noted it has a pronounced effect on friction and wear.

Lubricated Surfaces

Aluminum is an extremely chemically active element and it might be expected to interact very readily with lubricants. Some friction and wear experiments were conducted with iron and iron containing 10-atomic-percent aluminum to indicate the effect of the aluminum on lubricant-surface interactions. The results of these experiments are presented in figures 6 and 7.

In figure 6 the coefficient of friction remained relatively unchanged with the additions of 0.05- and 0.1-percent stearic acid to hexadecane. At a stearic acid concentration of 0.25 percent, the friction decreased to 0.13; and at an acid concentration of 1.0 percent, the friction reached a value of 0.10. With 10-atomic-percent aluminum in the alloy, the addition of as little as 0.05-percent stearic acid to hexadecane was sufficient to decrease the friction coefficient from 0.45 to 0.11. The reaction rate of stearic acid to the alloy surface is increased by the presence of the aluminum.

It is of interest that in figure 6 the friction for the iron-aluminum alloy in hexadecane was about twice the value obtained for iron. With the addition of 0.05-percent stearic acid, the iron friction remained unchanged, while that for the alloy decreased to about one-half the value obtained with iron. The more chemically active aluminum forms aluminum stearate more rapidly than iron can form iron stearate.

The data of figure 7 indicate wear results over the same range of stearic acid concentrations. The decrease in wear with stearic acid additions parallels the friction results. The wear of iron was reduced by a factor of at least 4; while with the iron-aluminum alloy, wear decreased over 100 times. These results indicate that not only the activity of the lubricant, but also the chemical nature of the metallic elements that

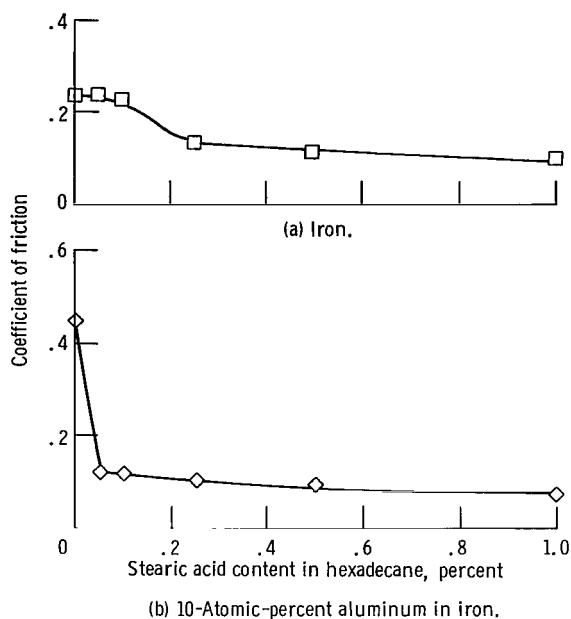


Figure 6. - Effect of stearic acid concentration in hexadecane on friction coefficient for iron and for a 10-atomic-percent-aluminum - iron alloy. Sliding velocity, 3.8 centimeters per second; load, 250 grams; 23° C for 1 hour in an argon atmosphere.

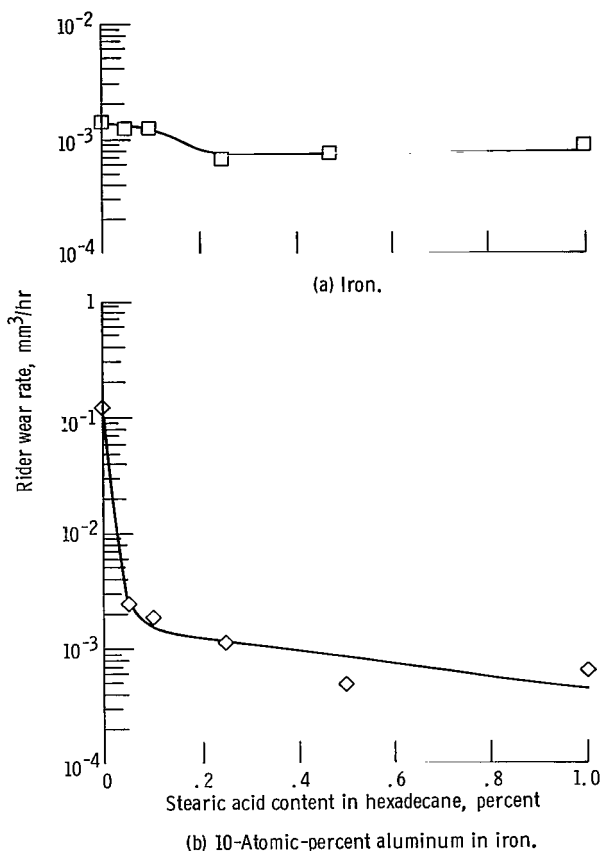


Figure 7. - Effect of stearic acid concentration in hexadecane on rider wear rate for iron and a 10-atomic-percent-aluminum - iron alloy. Sliding velocity, 3.8 centimeters per second; load, 250 grams; 23° C for 1 hour in an argon atmosphere.

are actually present on an alloy surface, are important in reducing wear.

The friction and wear data were obtained for alloys containing varying amounts of aluminum and sliding under hexadecane and under hexadecane containing two concentrations of stearic acid. The results obtained in these experiments are presented in figures 8 and 9.

In figure 8 the coefficient of friction increases markedly in hexadecane with the addition of 10-atomic-percent aluminum to iron. This is similar to the result obtained in figure 3 with dry sliding. At 20- and 25-atomic-percent aluminum, in contrast with dry sliding data, friction decreased from the value obtained with the 10-atomic-percent-aluminum alloy. These results indicate an interaction of the aluminum with the simple straight-chain hydrocarbon.

With 0.1-percent stearic acid in the hexadecane, the friction for the 10-atomic-percent-aluminum alloy decreased markedly from the value obtained in hexadecane.

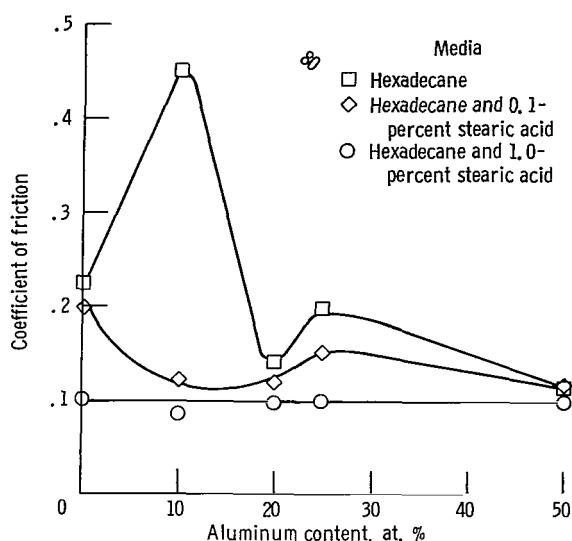


Figure 8. - Coefficient of friction for various iron-aluminum alloys in three media. Sliding velocity, 3.8 centimeters per second; load, 250 grams; 23° C for 1 hour and an argon atmosphere.

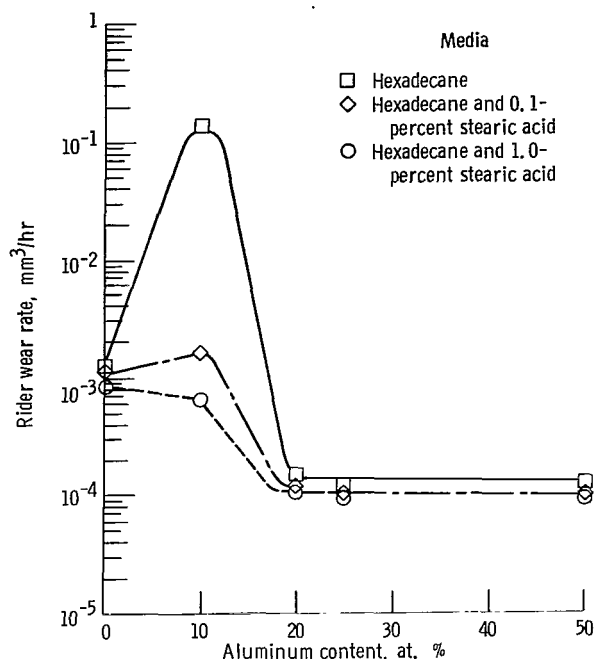


Figure 9. - Rider wear rate for iron-aluminum alloys in three media. Sliding velocity, 3.8 centimeters per second; load, 250 grams; 23° C for 1 hour in an argon atmosphere.

Further, the value was less than that obtained with iron. The very active chemical nature of the aluminum enhances a reduction in friction over results obtained in the absence of such a material. The friction for iron decreased only slightly from approximately 0.25 in hexadecane to 0.20 in hexadecane containing 0.1-percent stearic acid. The friction of the 10-atomic-percent-aluminum alloy decreased from approximately 0.5 to 0.13 with the addition of 0.1-percent stearic acid in hexadecane.

With 1.0 percent of stearic acid in hexadecane, there is more than sufficient stearic acid present to satisfy the need to provide a metal stearate protective film. And therefore, the friction coefficient is essentially the same for the iron and the iron-aluminum alloys. Where the concentration is sufficiently high, the kinetics of reaction and the thermodynamic stability of the surface film are not as critical as at lesser concentrations.

The data of figure 8 indicate that not only the activity of the lubricant but the reactivity of the surface is of importance. The presence of the aluminum in the iron and its equilibrium segregation to the surface has a pronounced effect on friction behavior. Thus, a factor that should be considered in lubricant selection is not the alloy but the alloy constituents that may be present on the surface and their affinity for the lubricant.

Wear data at various aluminum concentrations in the presence and absence of surface-active stearic acid are presented in figure 9. Just as with friction, wear in-

creased markedly in hexadecane with the addition of 10-atomic-percent aluminum in iron. The wear increased 100 times. The wear with the 20-, 25-, and 50-atomic-percent alloys was 1000 times less than that obtained with the 10-atomic-percent alloy and nearly 10 times less than that obtained with iron.

The wear values in figure 9 are rider wear rates. The profile of the disk surfaces in hexadecane for iron and for two of the alloys are presented in figure 10. The increase in surface wear with the addition of 10-atomic-percent aluminum to iron is obvious from the surface profile traces. The addition of 20-atomic-percent aluminum, however, results in a marked decrease in wear. The mechanical properties of these alloys are markedly different.

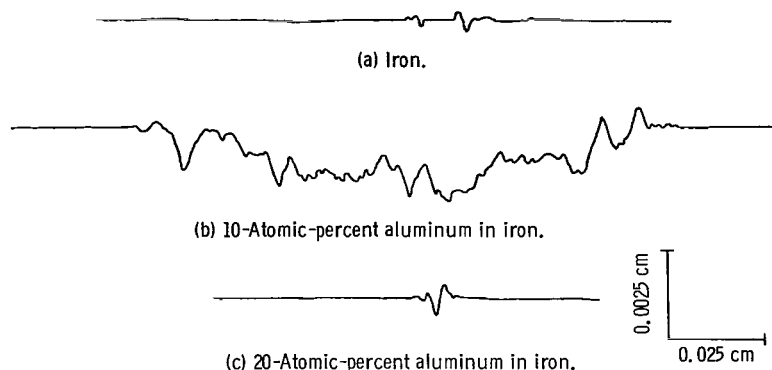


Figure 10. - Surface profile traces indicating surface damage to iron and iron-aluminum alloys after sliding in hexadecane. Sliding velocity, 3.8 centimeters per second; load, 250 grams; 23° C for 1 hour in an argon atmosphere.

The greatest changes in wear rate in figure 9 occurred with the 10-atomic-percent-aluminum - iron alloy when stearic acid was added to the hexadecane. Again the strong chemical reactivity of the aluminum provided a protective surface film to reduce adhesive wear. The differences in wear between the 10-atomic-percent-aluminum alloy and the alloys with higher concentrations of aluminum, with stearic acid present, can be related to the differences in mechanical properties. With the 10-atomic-percent alloy the surface is 80 percent covered with aluminum. The higher concentration alloys can only increase the surface coverage by 20 percent, which as shown in figure 4 will not markedly influence friction. The mechanical properties of these alloys are, however, markedly altered. The 10-percent-aluminum alloy has about eight times the elongation, 58 percent the tensile strength, and 60 percent the yield strength of the 20-atomic-percent-aluminum alloy (ref. 9).

CONCLUSIONS

Based on the friction and wear studies in this investigation with iron-aluminum alloys the following conclusions are reached:

1. The presence of aluminum in iron markedly alters the friction and wear behavior of iron both unlubricated and lubricated. With 10-atomic-percent aluminum, the aluminum increases friction and wear both dry and in hexadecane. The presence of the aluminum increases the reactivity of the surface with stearic acid.
2. Aluminum alloyed with iron undergoes equilibrium segregation to the alloy surface. With only 10-atomic-percent aluminum in the bulk, the surface can be covered with 80-percent aluminum as indicated by Auger analysis.
3. Order-disorder reactions in the iron-aluminum alloys Fe_3Al and FeAl did not affect friction and wear.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 25, 1971,
129-03.

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